

Airborne Magnetometry Surveys for Detection of Unexploded Ordnance

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Unexploded ordnance (UXO) contamination is a high-priority problem for the Department of Defense (DoD). As used here, UXO refers to explosive, propellant, or chemical-containing munitions that are armed, fired, and remain unexploded because of malfunction. Approximately 1,400 DoD sites, comprising about 10 million acres, are known to or are suspected of containing UXO. A typical site is thousands of acres; many exceed 10,000 acres, a few are several hundred thousand acres. Most of these sites are Formerly Used Defense Sites (FUDS) for which the DoD retains liability for ordnance. Remediation of such large areas would cost tens of billions of dollars. However, according to some estimates, no more than 20 percent of those 10 million suspected acres are actually contaminated with UXO. Thus, identifying a technology or combination of technologies to accurately delineate the contaminated areas on each site would significantly reduce the actual area that would require a site investigation and response. This would allow limited cleanup resources to be used more effectively.

INTRODUCTION

The Defense Science Board (DSB) Task Force on Unexploded Ordnance issued a series of recommendations about this problem in their December 2003 report.¹ Recommendation 1 was "Institute a national area assessment of the identified 10 million acres [of land involved]." They elaborate on this recommendation, saying "The Task Force envisions an intensive five-year campaign to assess all 10 million acres with the goal of delineating where the UXO *are* and where they *are not*. This campaign would use the full range of techniques and instruments including the helicopter-borne sensor where applicable."

One of the helicopter-borne sensors to which they refer is the Naval Research Laboratory's airborne magnetometer array whose development was supported by the Environmental Security Technology Certification Program (ESTCP). This airborne system was developed as an adjunct to the vehicular Multi-sensor Towed Array Detection System (MTADS) and is often referred to as airborne MTADS.

TECHNOLOGY DESCRIPTION

Sensors

The airborne array (Fig. 1) comprises seven magnetometers spaced at 1.5 m in a 9-m boom mounted just forward of the blade tips of a Bell LongRanger helicopter.² The sensors are cesium-vapor total-field magnetometers that measure localized perturbations to Earth's magnetic field caused by ferrous metal, in

this case UXO. The magnetometer signals are sampled at 100 Hz that, combined with a typical survey speed of 10 m/s, results in a down-track measurement spacing of ~10 cm.

Sensor positions are determined by using two GPS antennas configured as a master/slave pair. The master receiver receives corrections from a fixed-base station; it reports real-time kinematic (RTK) positions at 20 Hz with an accuracy of ~5 cm and the vector to the slave at 10 Hz with similar accuracy. To obtain height-above-ground measurements, which are useful for the data analyst, a laser altimeter is mounted under the body of the helicopter, and acoustic altimeters are mounted alongside the laser altimeter and under the two GPS antennas. Altitude readings are recorded at 10 Hz. All sensor readings are time-stamped with a time that can be related to the UTC time reported in the GPS position string.

All sensor outputs are sent to a data acquisition computer that is mounted in the rear starboard seat of the helicopter. During testing and initial surveys, an operator in the rear port seat monitored the survey progress. In later production demonstrations, the data were recorded on the data acquisition computer and sensor health and status information was telemetered to a ground observer. This minimized the number of personnel in the aircraft for safety considerations.

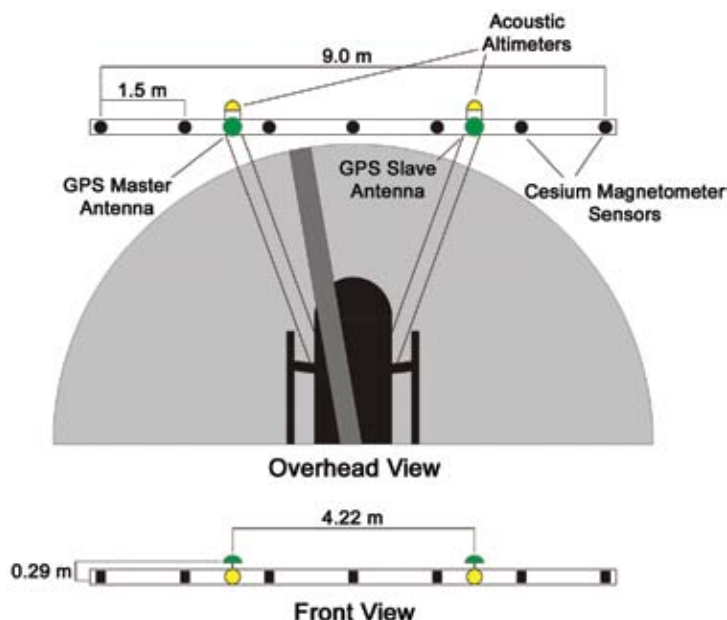
Survey Data Acquisition

The helicopter flies preplanned survey lines by monitoring a sunlight-readable navigation guidance display developed specifically for this program. The

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FIGURE 1

Major system components of the airborne magnetometer array. The seven total-field magnetometers are mounted just forward of the blade tips and are spaced at 1.5 m across track. Sensor positions are derived from a pair of GPS antennas and height above ground is derived from acoustic altimeters mounted under the GPS antennas and under the body of the aircraft and a laser altimeter mounted under the aircraft.



display is mounted to the right of the instrument panel. It is in the field of view of the pilot but does not interfere with the pilot's ability to see the entire forward boom and the ground immediately ahead of the aircraft.

The navigation guidance display (Fig. 2), provides the pilot left-right indicators, an altitude indicator, an automatic line number increment, a color-coded flight swath overlay, and the ability to zoom the map scale in or out as desired. The survey course-over-ground is plotted in real time on the display using information from the GPS receivers. This allows the pilot to respond rapidly to both visual cues on the ground and to the navigation guidance.

Survey lines typically have a spacing of 7 m. This allows for a significant overlap of adjacent survey passes of the 9-m sensor boom and ensures that there are no gaps in survey coverage, even in moderately windy conditions. Since the amplitude of the anomaly signal measured by the magnetometers falls off as the third power of the target-to-sensor distance; it is important to keep the sensors as close to the ground as possible. Our nominal survey altitude is 1.5 m, although this can be relaxed somewhat when searching only for large targets. Figure 3 shows the system conducting a survey at the Badlands Bombing Range Impact Area in southwestern South Dakota.

The cost of chartering the helicopter is one of the largest expenses in a survey. For this reason, we make every effort to minimize the time that the aircraft is flying without data being collected. Because the survey ranges are former military test and training ranges, a typical survey site is many miles from the nearest

town. We normally place the aircraft at the nearest community airport, often 10 to 20 miles from the survey site. To avoid having to fly this round trip for each refueling (2 to 2½ hours) we base a jet fuel tank on the survey site itself. Thus, at each refueling interval, the pilot can take a rest break while the aircraft is being refueled and no flight time is lost. On a typical operational day we can survey 400 acres. By employing two pilots and extra support crew, we have achieved survey coverage of 800 to 900 acres a day.

Data Preprocessing

All survey data are transferred using removable media to a field computer for inspection and processing. The analyst initially inspects the files for completeness and data quality. Typically, a low-pass filter is applied to the magnetometer data. This removes the effects of platform-induced directional errors and large-scale geologic interferences.

The primary platform-induced interference is that associated with the rotor hub of the aircraft. The hub assemblies are magnafluxed during overhauls to inspect for stress and fatigue cracks and often are not completely demagnetized following the overhaul. The primary noise appears at 6.5 Hz (corresponding to the 390 rpm fixed rotation rate of the blades) and at 13 Hz. There is also a significant noise spike at 25 Hz, which we believe is associated with a standing-wave vibration of the forward boom assembly. All of these frequencies are significantly above the frequencies associated with UXO targets; therefore we remove them by applying a series of narrow notch filters.

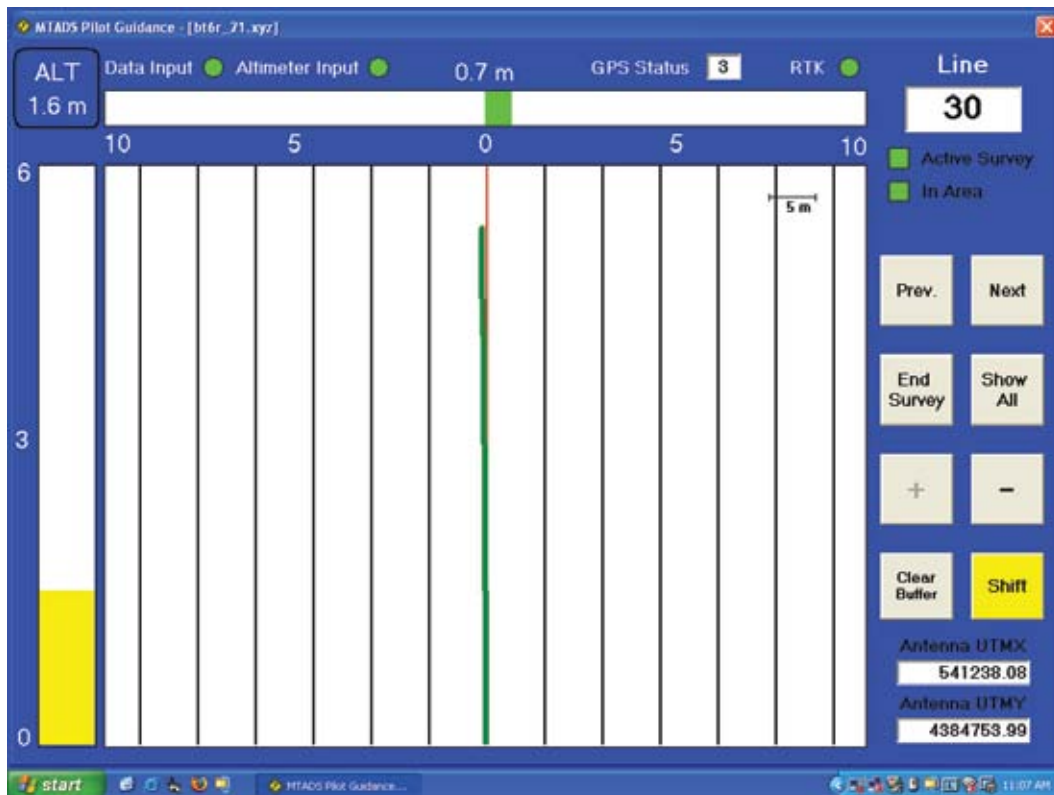


FIGURE 2

Detail of the pilot-guidance display showing the pilot flying up line 30 (highlighted in red) of the preplanned survey. The actual position of the aircraft is plotted in green on the survey grid and an indication of left-right position is shown by the color bar above the map. Altitude (1.6 m, in this case) is indicated by the color bar on the left.



FIGURE 3

Airborne magnetometer array mounted on a Bell LongRanger helicopter performing a geophysical survey.

The final step in data preprocessing is assigning a position to each magnetometer sensor reading. We accomplish this directly by using the measured boom position and orientation. The altitudes derived by this method are relative to the ellipsoid, not the Earth's surface. This has proven inconvenient for two reasons. The analyst needs an estimate of target depth below the surface to assist in classifying detected targets as UXO (which are typically buried) and fins and fragments (which are often at or near the surface). In addition, remediation crews are much more efficient if they have an accurate depth estimate to guide their removal digs, e.g., should they use a shovel or a backhoe to uncover the object. To connect the height-above-ellipsoid values to height-above-ground, we construct a Digital Elevation Model (DEM) using the altimeter readings.

Figure 4 illustrates the main components used to derive a DEM. Two adjacent passes of the array are shown, each at a slightly different elevation and orientation. For each pass, altitude data are collected from the laser altimeter and the three acoustic altimeters (the third is collocated with the laser altimeter under the body of the aircraft). These data allow us to derive a digital elevation model referenced to the ellipsoid and then to reference the estimated target locations in the earth to this ground surface model.

Data Analysis

The preprocessed mapped data files, displayed as a magnetic anomaly image, are given to an analyst for target selection and analysis. Working systematically through the survey data, the analyst visually identifies anomalies that are consistent with compact ferrous objects (i.e., UXO), boxes an appropriate subset of the data, and submits the selected data to a seven-parameter model match routine for estimating magnetic dipole parameters. From the amplitude of the anomaly signal and the spatial extent of the anomaly, an estimate of target depth and size is derived.

An example of this is shown in Fig. 5, which plots an anomaly selected from a survey of the Browns Island Range at Camp Lejeune, North Carolina. The measured survey data are plotted as an interpolated image on the left-hand side of the figure; actual measurement locations are indicated by the dots. We typically collect 50 to a few hundred measurements over each anomaly. These measurements are submitted to the model-match routine, and the results are plotted on the right-hand side of the figure. As can be seen, the agreement is excellent. The modeled data correspond to a target roughly the size of a 500-lb bomb buried 90 cm below the surface. The expected targets on this range are 105-mm projectiles and 500-lb bombs.

DEMONSTRATION RESULTS

Individual Ordnance Detection

The airborne magnetometer system has been tested and demonstrated at a number of prepared and live ranges. Reference 2 provides a complete list of areas surveyed and individual discussions of the findings. The primary objectives of a UXO survey system are:

- detect all UXO;
- predict accurate sizes, locations, and depths to maximize the efficiency of recovery (remove less dirt from each hole) and allow for leaving small, shallow fragments in the field; and
- collect data of sufficient quality to support classification (UXO vs not-UXO) of the detected targets.

For ranges with reasonably low levels of geologic interference containing ordnance larger than a 2.75-in. rocket warhead, the airborne system can meet these objectives. We have demonstrated probabilities of detection (P_D) of 95% or greater for these targets.

Figure 6 shows an example of the target location accuracy of the system. These are data from a survey of Target S1 on the Isleta Pueblo just south of Albuquerque, New Mexico. This was a target used for training high-speed bomber pilots during World War II. The airborne system surveyed ~1,500 acres centered on the bombing target, and the vehicular system covered the center 150 acres for validation purposes. Two areas away from the target were selected for remediation and more than 300 targets were dug in each area. Data from the central area are shown in Fig. 6. The left-hand panel shows the difference between the predicted position and the actual, measured position of the target plotted on a polar plot. Most of the targets were located within 0.5 m, and there is no obvious directional bias of the predicted position. The miss distance is quantified in the right-hand panel as a histogram. The mean miss distance was just under 50 cm, and 90% of the targets were within 90 cm of the prediction. The Isleta site provided more challenging geology than typical, and P_D s were in the range of 65%.

Wide Area Detection

When used in the Wide Area Detection role envisioned by the DSB task force, the goal is locating targets on a large range and, by extension, areas that are free of UXO contamination; detecting individual anomalies is less important. In this case, we are looking for concentrations of anomalies with enough resolution to accurately determine the extent of UXO-contaminated

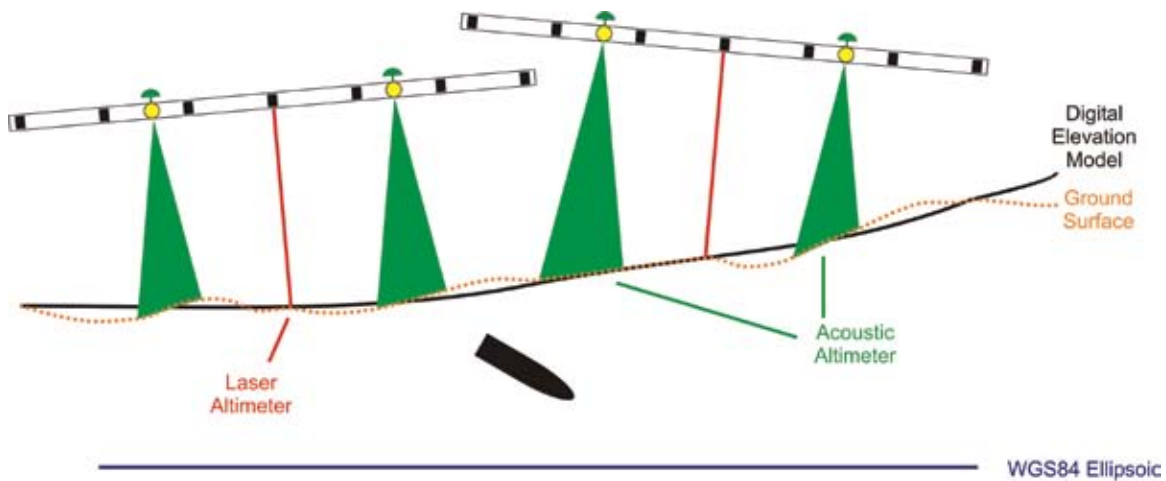


FIGURE 4

Schematic showing the process of deriving a Digital Elevation Model (DEM). The GPS-derived sensor positions are referenced to the Ellipsoid. This is all that is required to locate the UXO, but it has proven difficult for the analyst to judge the reliability of the model match without reference to ground level. Two adjacent passes of the array at slightly different elevations and orientations are shown. The primary altitude measurement is the laser altimeter (red line) but these data are relatively sparse. We supplement these with the acoustic altimeter data to derive the DGM.

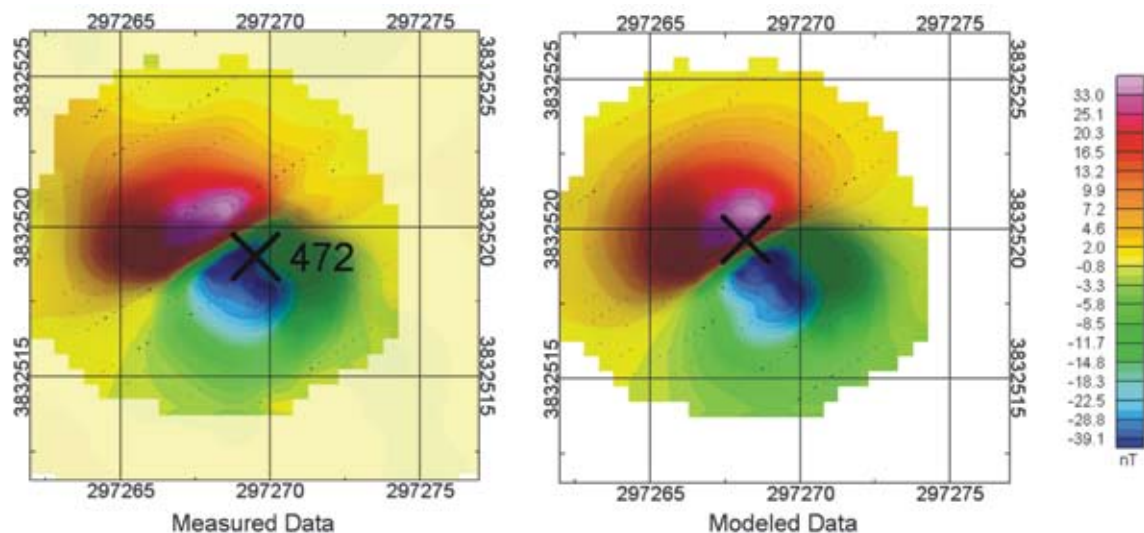


FIGURE 5

Example of measured anomaly data and resulting model-match results. Measured data are on the left and modeled data are on the right. On both plots, the actual measurement locations are indicated by individual dots.

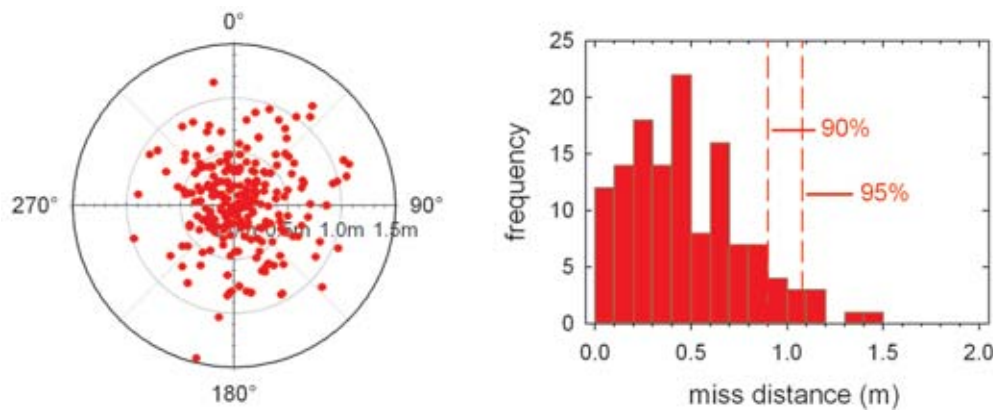


FIGURE 6

Location performance of the airborne system for remediated targets from a survey of Target S1 on Isleta Pueblo, New Mexico. The left-hand plot shows the difference between predicted target positions and actual position plotted on a polar plot. There is no obvious directional bias to the predictions. The right-hand plot is a histogram of miss distance for the 338 targets dug in this demonstration. The mean miss distance is 49 cm; 90% of the predictions are within 90 cm.

areas so that they can be delimited from UXO-free areas.

In the summer of 2005, the Environmental Security Technology Certification Program, with direction from the Congress, conducted a Wide Area Assessment Pilot Program. Demonstrations were conducted at three sites, Pueblo Precision Bombing Range 2 near La Junta, Colorado; former Kirtland Precision Bombing Ranges N1, N3, N4, and New Demolitions in Albuquerque, New Mexico, and Victorville Precision Bombing Range Y near Palm Springs, California. The NRL airborne array was flown by Sky Research, Inc., of Ashland, Oregon as one component of these demonstrations.

Each demonstration site was roughly 5,000 acres. Figure 7 shows data collected on the northern portion of the Kirtland site. Historical records on this site discuss the existence of two practice bombings targets and one target for high-explosive bombs. These targets can be seen in the upper left and lower right corners of the area presented.

Historical records also mention a Simulated Oil Field Target, but the location was not known. Survey data reveal a concentration of anomalies in the middle of the area shown in Fig. 7. The inset is a 15-acre blowup of this area. Hundreds of individual magnetic anomalies are in this area, indicating that this is likely the position of the unlocated target. Intrusive investigations carried out in the spring of 2006 confirmed this assignment.

A close analysis of the data in Fig. 7 reveals additional detail. The target in the northwest corner of the site is obviously composed of a primary, central

target with several smaller target areas surrounding the central region. This is an example of the resolution required to precisely bound the edges of targets and return as much land as possible to productive use.

SUMMARY

We have designed, constructed, and demonstrated a helicopter-borne magnetometer array for the detecting buried UXO. The system has proven to be useful for both detecting and accurately locating individual UXO items the size of 2.75-in. warheads and larger and for detecting and bounding target areas on large ranges. This highly successful system will be an integral part of any national assessment of UXO contamination on Closed, Transferred, and Transferring Ranges.

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[Sponsored by ESTCP]

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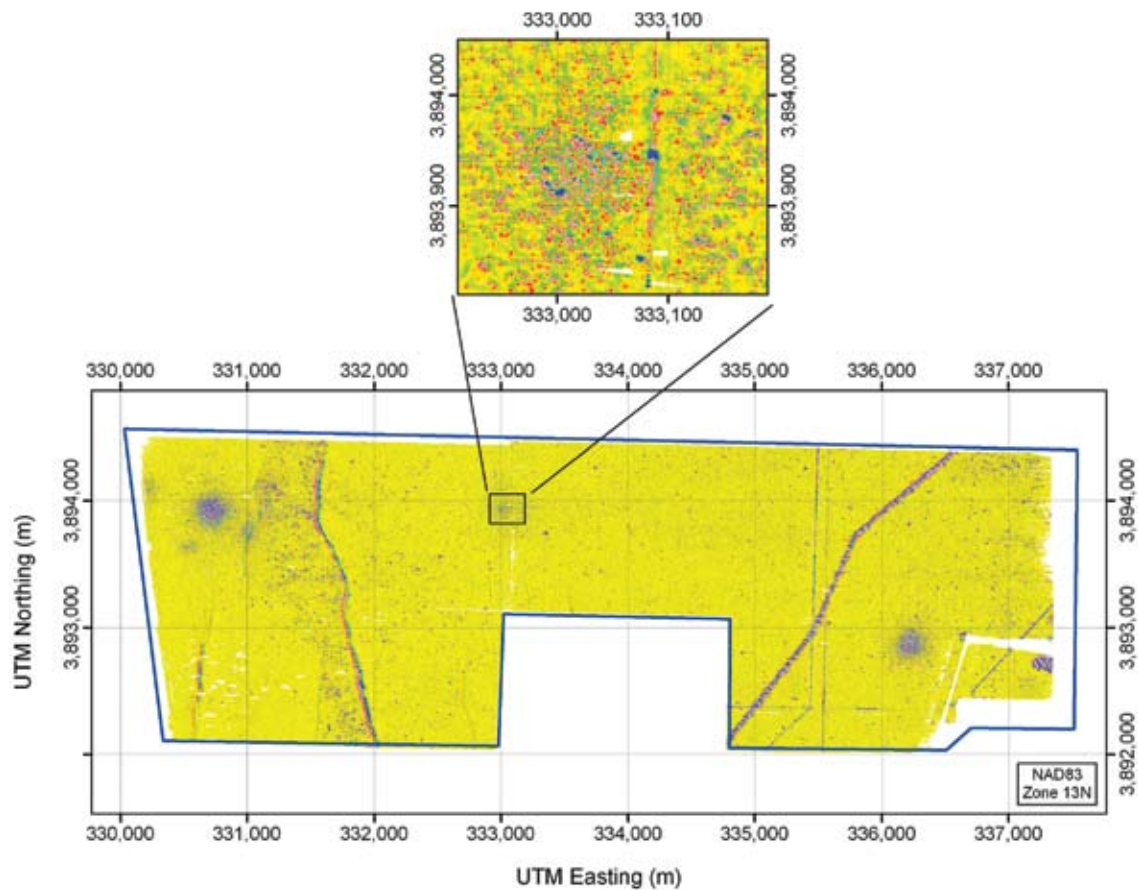


FIGURE 7

Survey results from the northern section of former Kirtland Targets N1, N3, N4, and New Demolitions Area. The historical documents for this site discussed a Simulated Oil Field Target but the position was not known. The inset is a blow-up of a 15-acre portion of the site and shows the large number of UXO targets discovered. This established the location of the Simulated Oil Field Target.